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ESTIMATING RECOVERABLE OIL VOLUME REMAINING IN WEEKS ISLAND AS A FUNCTION OF PUMP RATE AT THE TIME OF PUMP CAVITATION

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ABSTRACT

The recoverable volume of crude oil in Weeks Island at the time of pump cavitation is estimated to be approximately 1% of the initial oil inventory. Even though uncertainties in the calculational model are large, the final result is expected to be within a factor of 2 or 3 of the actual value.

Problem Description

Problem

Approximately 73 million barrels (MMBBL) of crude oil are stored in the Weeks Island facility as part of the Strategic Petroleum Reserve (SPR) program. In order to effectively complete an oil drawdown at the facility, the Department of Energy (DOE) recognizes that possible problems should be identified before they occur, and that methods which mitigate their effects need to be incorporated into the drawdown schedule.

Sandia National Laboratories Albuquerque (SNLA) has been requested by DOE to investigate one such problem. Specifically, we were asked to estimate the volume of recoverable oil remaining in the facility as a function of pump rate at a time corresponding to pump cavitation caused by insufficient oil at the pumps to maintain the desired pump rate. The findings of our investigation are detailed in the remainder of this report.

Overview	Eleven pumps located in the Weeks Island oil storage sump are designated to be used for oil drawdown operations. If the pumps cavitate before the drawdown operation is complete, a certain quantity of oil (recoverable residual oil) will remain in the facility. The purpose of this study is to identify conditions that can lead to pump cavitation, to estimate the volume of recoverable residual oil if cavitation occurs, and to recommend operational procedures for pump control during drawdown.
Conditions for Cavitation	Cavitation of the pumps at Weeks Island during oil drawdown operations can occur for two reasons: o insufficient net positive suction head (NPSH)(oil boils due to low pressure conditions and cavitates the pumps). o insufficient oil depth at the sump to maintain the desired flow.

continued

Since oil withdrawal plans at Weeks Island call for injection of an inert gas to maintain pressure, cavitation due to insufficient NPSH should not occur.

However, cavitation can occur near the end of drawdown if pump operations continue unchanged.

Report Analyses

In the remainder of this report we will describe the results of an approximate technique for calculating the volume of recoverable oil remaining in Weeks Island as a function of pump rate at the time when the pumps can be expected to cavitate due to insufficient oil depth at the sump. (No attempt is made in this report to estimate the non-recoverable quantity of oil in the mine due to such processes as crack filling or granular salt penetration.)

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continued

Note

Even though the pumps cavitate, some additional oil can be recovered by pumping at a reduced rate. Theoretically, all recoverable residual oil can be recovered by a sequence of reduced pumping steps. However, in practice, variations in the floor elevation will preclude a complete recovery.

Table of Contents

Contents

The material presented in this report is arranged in the following order:

Summary

The following points summarize the findings of this study:

- The model used in our calculations is not precise, but should yield results for the recoverable oil at the time of cavitation which ace within a factor of two or three of the actual values.
- Errors ace introduced in the calculation by
  (1) using an "equivalent" channel to represent the wall/pillar geometry of Weeks Island,
  (2) uncertainties in the Manning roughness coefficient for the equivalent channel, and
  (3) pseudo steady-state open channel flow hydraulics in a time dependent problem.
- Residual recoverable oil volumes remaining in the facility when the pumps cavitate can be expected to be small at the design recovery pump rate (about 1% based on an initial total volume of 72.9 MMBBL).[1]

continued

- o The recoverable residual oil volume can be reduced by decreasing the pump rate at the appropriate time.
- o The volume of oil in the service shaft sump (less than 1000 BBL) is too small to significantly affect the calculations presented in this report.
- o The additional time required to reduce the recoverable residual oil is small.
- o Curvature of the oil surface is most pronounced at the largest pump rate, but even then, the maximum difference in depth is on the order of one foot.
- o A more complex mathematical model is not likely to produce significantly better results due to the problem of having to define an equivalent channel for the Weeks Island wall/pillar geometry. Use of an open channel matrix solver might produce more accurate results. However, the amount of time required to solve the problem in this manner precluded its use (code development plus input preparation).

Method

The following list summarizes the steps used in calculating the quantity of recoverable oil as a function of pump rate at the time corresponding to pump cavitation:

- An equivalent open channel was developed for the Weeks Island wall/pillar geometry. An equivalent channel was necessary in order to simplify and expedite the calculation.
- For a given flow rate (Q) and equivalent channel geometry, the critical depth at the sump boundary (Yc) was determined.
- The time required to achieve a depth of Yc at the brink of the sump was estimated using a linear model and mass conservation.
- Normal depth in the equivalent channel (Yo) was calculated using the Manning equation.
- The recoverable oil volume at the time of pump cavitation was estimated by calculating the volume under the oil surface profile.

Assumptions

The method used to determine the volume of recoverable oil in Weeks Island as a function of pump rate at a time when the pumps are expected to cavitate makes use of the following assumptions:

- The wall/pillar geometry of Weeks Island can be modeled using an equivalent prismatic (constant cross-section) rectangular open channel. This type of channel was selected in order to make the calculation as simple as possible and because no significant differences were found when a nonprismatic channel (converging section) was employed in the calculation.
- The channel can supply the desired flow rate as long as the depth of the oil at the brink of the sump exceeds the channel's critical depth.
- There is sufficient time for the oil surface to assume a steady-state profile as drawdown proceeds (Q is constant along a reach of the channel).

continued

Assumptions of the Calculation continued

- The oil surface profile is Mild type 2 (M-2).[3] (The depth of the oil at the brink of the sump is critical and the depth of the oil upstream of the sump asymptotically approaches the normal depth value.)

Equivalent Channel Description

Equivalent Channel

The equivalent channel used to model the wall/-pillar geometry of Weeks Island[2] (shown in Figure 1 below) uses for simplicity a prismatic, rectangular geometry. The height of the equivalent channel is the same as the average height of the Weeks Island rooms, 75 ft.[2] The width of the equivalent channel is set equal to the circumference of the withdrawal sump (approximately 28 ft.).[2] This width was selected for two reasons: (1) the sump hole behaves like a drop-inlet open channel structure whose equivalent width is equal to its circumference, and (2) because use of a narrow width channel provides a conservative estimate of the volume of oil remaining in the facility when critical depth is reached at the brink of the sump. The length of the channel is calculated from the volume of oil contained in the lower section of Weeks Island as of January, 1984 (49.4 MMBBL).[1] A prismatic rectangular geometry was chosen for the following reasons:

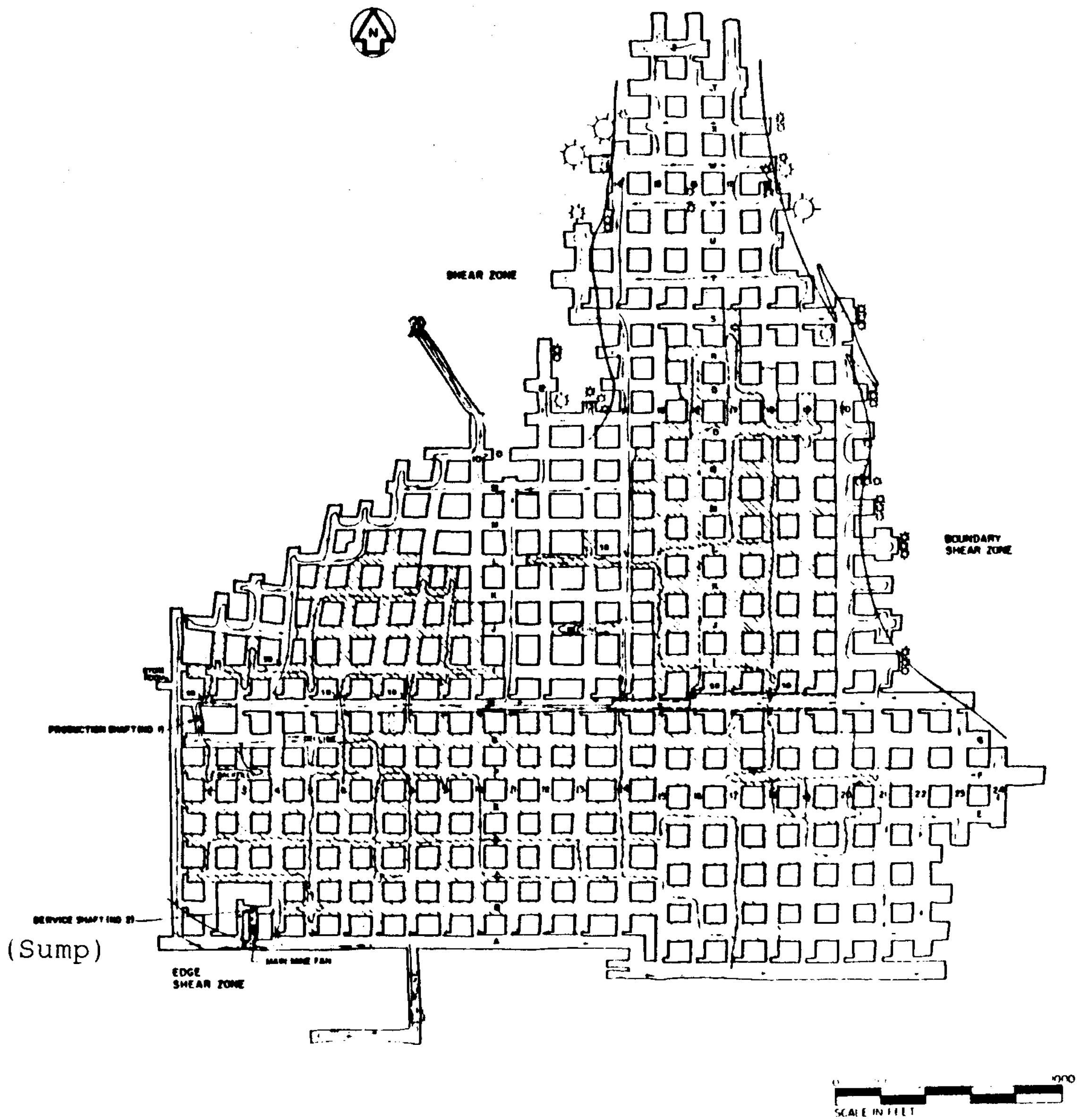
continued

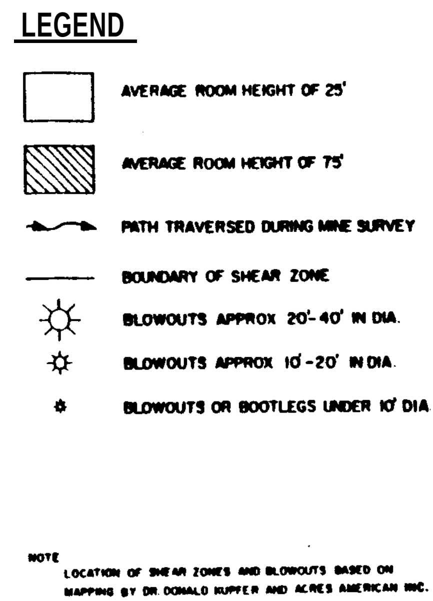
Equivalent Channel Description continued

- A rectangular channel has simple hydraulics.
- A rectangular channel is similar to the actual flow channels at Weeks Island.
- Results obtained using a non-prismatic channel (converging section) were essentially the same as the results obtained with a constant cross section channel.

Wall Effects

The magnitude of the effects caused by the mine walls can be estimated by investigating the equivalent hydraulic conductivity of the wall pillar geometry. Treating the wall pillar geometry like a porous media leads to hydraulic conductivities on the order of 10^{10} ft./day (Carman-Kozeny and Brinkman model).[7,8] The effects of the walls for such a large value of hydraulic conductivity should be small. We can therefore reasonably treat the wall/pillar geometry as a single open channel.





(From Acres American, Inc., 1977, National Strategic Oil Storage Program, Weeks Island Mine - Geotechnical Study, Report To Gulf Interstate Engineering Company under contract No. FEA-1251-75 to the U. S. Federal Energy Administration)

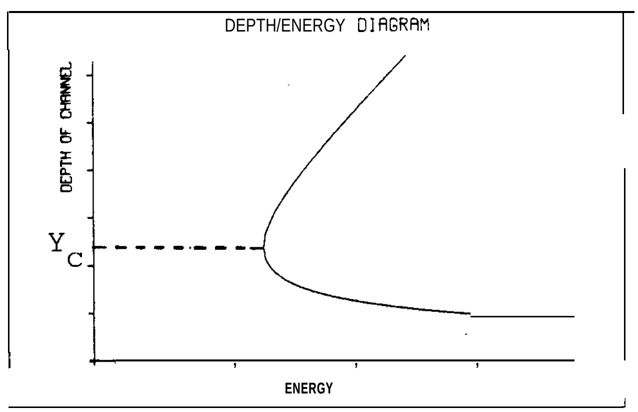
Figure 1. Weeks Island Lower Level.

Definition

Critical depth is the depth of the flow in the channel for which the channel energy is minimized, and the flow rate for the channel geometry is maximized. (3)

Diagram of Channel Depth Versus Energy

The relationship between channel depth and energy is shown in the figure below.



Importance of Critical Depth

The channel critical depth corresponds to the depth for which the channel flow is maximized. If the pump rate is not decreased once critical depth is achieved at the brink of the sump, the channel will be unable to maintain the desired flow, and the pumps will cavitate.

continued

Critical Depth Calculation continued

Calculating Critical Depth

For a rectangular channel, critical depth, Yc, is calculated from the following expression:[3]

$$F_R^2 = \frac{Q^2 W}{gA^3} = 1$$

where Q = channel flow

g = gravitational constant

A = channel area = W x depth

F_R = Froude number = ratio of inertial to gravitational forces

and W = channel width

Yc is thus given by the simple relation:

$$Y_c = \left(\frac{Q^2}{gW^2}\right)^{1/3}$$

Time to Achieve Critical Depth

Time to Achieve Critical Depth

A simple mass balance relationship is used to estimate the amount of time required to reach a depth of Yc at the brink of the sump:

$$\text{time} = \frac{\text{volume of upper Level} + (h - Yc) * W * L}{Q}$$

where the volume of the upper level = 23.5 MMBBL[1] and

h = height of the equivalent channel of the lower level = 75 ft.

W = width of the equivalent channel = 28 ft.

L = length of the equivalent channel = 132,190 ft.

Time Rate of Change of the Channel Depth

The time rate of change of the channel depth can be approximated by the following relationship:

$$\frac{dh}{dt} = \dot{h} = \frac{Q}{WL}$$

This relationship can be used to estimate how fast the depth of the oil at the brink of the sump is changing.

Oil Surface Profile	The oil surface drawdown curve for the equivalent channel in our calculations is assumed to be Mild type 2[3] (M-2).
Definition	The flow in a channel is classified as M-2 if the flow at one end of the channel reach is critical, and the depth of the flow asymptotically increases to the normal depth value going upstream of the critical channel section.
Arguments for Using an M-2 Profile	The flow in the model equivalent channel is assumed to be M-2 for the following reasons: o The bed of Weeks Island is nearly flat (bed slope $\simeq$ 1/3000). o The oil falls over a brink as it enters the sump hole. o Calculated normal depths exceed the critical depth.

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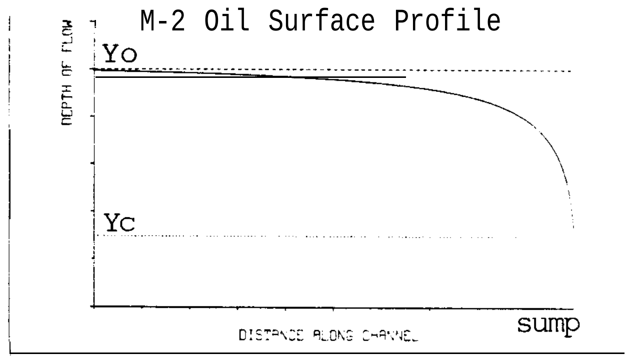
M-2 Profile

The following diagram shows the expected oil surface profile when the depth of the oil at the brink of the sump reaches the critical value.



The depth of the oil at the brink is Yc while the depth of the oil asymptotically approaches normal depth (the depth of the fluid in a channel having a flow rate Q and only subject to bed slope So) upstream of the sump.

Estimate of Recoverable Residual Oil

Integration of the oil surface profile when the depth of the oil at the brink of the sump is Yc provides an estimate of the recoverable residual oil in the facility. This oil cannot be recovered without cavitating the pumps unless the pump rate is decreased.

Normal Depth Determination

Definition

Normal depth in a channel is the depth fluid achieves for a flow rate Q under the action of bed slope S_o.

Normal Depth Determination

Normal depth in our equivalent channel is determined by employing Manning's equation:[3]

$$Q = \frac{1.49}{N} \frac{A^{5/3}}{P_w^{2/3}} S_o^{1/2}$$

where

Q = channel flow

A = channel cross-sectional area = W * Yo

P_w = channel wetted perimeter = W + 2 * Yo

so = bed slope = 1/3000

N = channel roughness = .03

Yo = normal depth

W = channel width

The above equation in terms of the normal depth is given by:

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continued

$$Q = \frac{1.49}{N} \frac{Wy_o^{5/3}}{(W + 2y_o)^{2/3}} S_o^{1/2}$$

An iterative scheme must be used to solve for the normal depth because of the transcendental nature of the above relationship.

Roughness Comment

The channel roughness used in the Manning equation was estimated to be .03. For water, the salt walls will have a roughness coefficient approximately equal to .015. The ratio of oil roughness to water roughness can be approximated as

$$\frac{N_{oil}}{N_{water}} \simeq \sqrt{\frac{f_{oil}}{f_{water}}}$$ where f = friction factor.

For smooth turbulent flow f is given by the Blasius expression as:[9]

$f = .316/R_e^{1/4}$ where R_e = fluid

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continued

Reynolds number $= \frac{\rho VD}{\mu} = \frac{VD}{\nu}$.

For equivalent flow,

$$\frac{N_{oil}}{N_{water}} \simeq \left(\frac{\nu_{oil}}{\nu_{water}}\right)^{1/8}$$ where ν = dynamic viscosity

At 20°C, $\frac{N_{oil}}{N_{water}} \simeq 2.2$

Therefore, a value of .03 was used for Manning's N.

Effect of N Variation

Varying N produced changes in the residual oil volume, but these changes were not excessively large (e.g., varying N from .02 to .04 at a flow rate of 590 MBBL/day produced a 50% change in the residual oil volume, 680 to 1040 MBBL – 1% to 1.4% of the total initial oil inventory.).

Estimating Residual Oil Volume

Instead of doing a point-by-point integration of the oil surface profile, the following approximation to the volume was used (see Figure 2):

- Between the brink of the sump and the point in the equivalent channel where the depth is equal to 0.95 * Yo (L), the volume is estimated as:

  Vol 1 = L * W * Yc + 0.5 * L * W * (Yo - Yc).

  (A depth of .95 Yo was arbitrarily chosen to divide the oil surface profile into two simply shaped geometric regions and to minimize the error introduced by not performing a detailed integration of the curve. For a Mild type 2 profile, any value between .90 to .99 Yo could have been used without significantly affecting the calculation).

- From the point in the channel where the depth is equal to 0.95 * Yo to the end of the equivalent channel (Xl), the volume of oil is estimated as:

  Vol 2 = Xl * W * Yo

continued

Determining the Location in the Channel where Depth = 0.95 * Yo

How to Find Where Depth = 0.95 Yo

The distance upstream from the brink of the sump to the point where the depth in the equivalent channel is equal to 0.95 * Yo can be readily calculated using a direct step method which is based on the conservation of energy: [3]

$$L = \frac{E_1 - E_2}{S_o - S_f}$$

where

E_1 = the energy in the channel at the brink of the sump. For a rectangular channel the energy at the brink of the sump (E_1) is given by $E_1 = 1.5 * Yc$. [6]

E_2 = the energy in the channel at the desired location (Y2 = 0.95 * Yo = depth of flow at point 2).

S_o = bed slope = 1/3000.

S_f = average channel friction slope between points one and two.

continued

The energy in the channel and the average friction slope are given by the following expressions:

$$E = Y + \frac{Q^2}{2gA^2}$$

$$S_f = \frac{V^2 \ N^2}{1.49^2 \ R^{4/3}}$$

and $U = (V1 + V2)/2$ = average channel velocity

$R = (R1 + R2)/2$ = average hydraulic radius of the equivalent channel = A/P,.

Calculational Results

Calculations

Table 1 lists the results of calculations performed for flow rates ranging from 0.25 to 60 ft^3/s (3.850 to 923 MBBL/day). Flow rates of 38.4 and 60 ft^3/s (590 and 923 MBBL/day) respectively correspond to the optimum drawdown flow rate and the flow rate achieved if all 11 pumps are operating in parallel at 2400 g/min[4].

Notes on Table I.

The following notes apply to the appropriate columns of Table 1:

- Time (column 4) - The time shown in this column represents the time needed to reach a depth equal to Yc at the brink of the sump and includes the time needed to empty the upper level of Weeks Island (volume of top/Q).
- Residual oil fraction (column 8) -- The residual oil fraction shown in column 8 of the table represents the fraction of recoverable oil remaining when the depth of the oil at the brink of the sump is equal to the critical depth.

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continued

- The last column of the table is an estimate of how fast the depth at the brink of the sump is changing in ft/day.

Figure 3

Figure 3 is a plot of the percent of recoverable residual oil (column 8 of Table 1 expressed as a percentage) as a function of flow rate when the depth of the oil at the brink of the sump is critical.

FIGURE 3

RECOVERABLE OIL AT CAVITATION

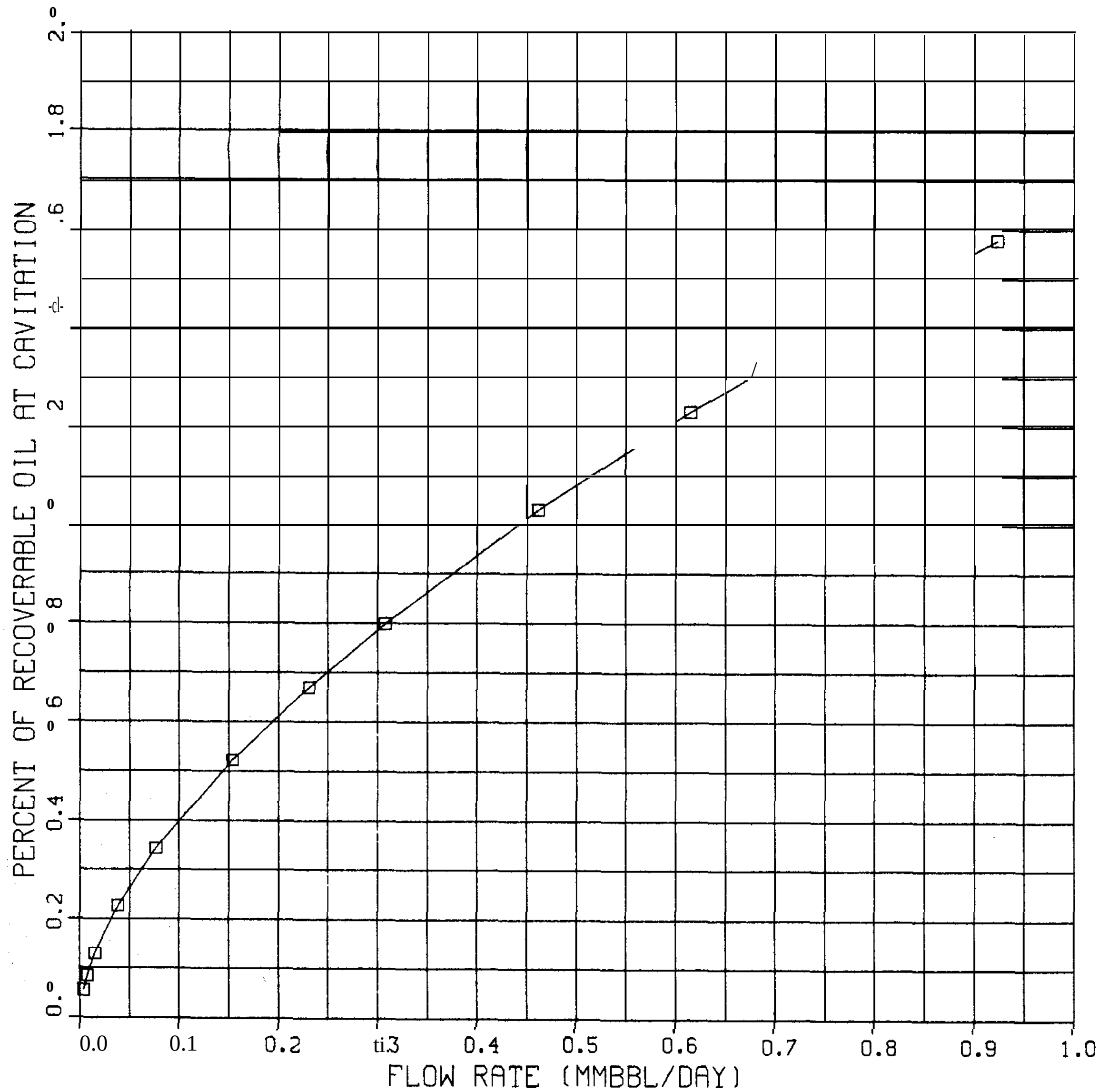
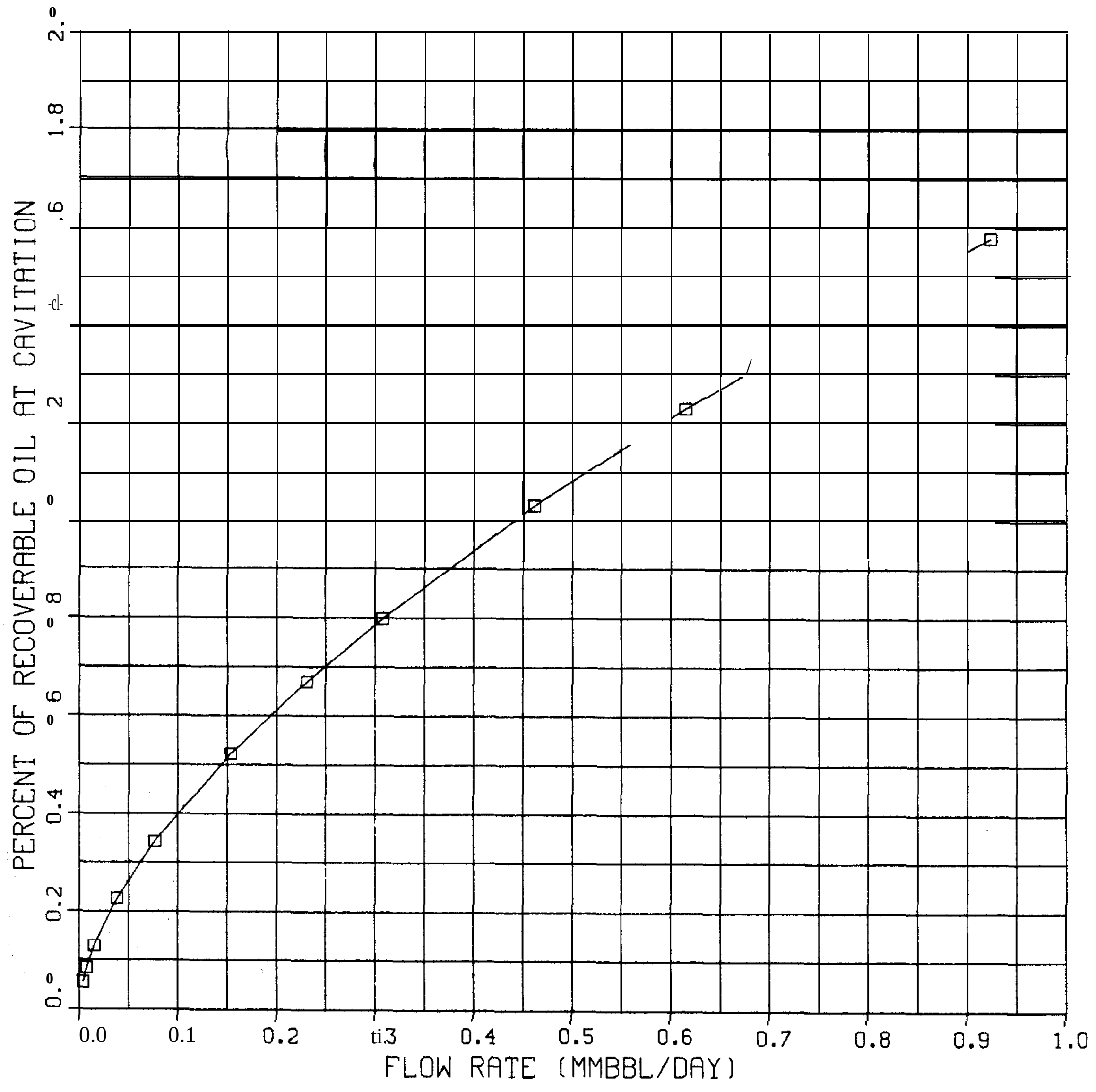


FIGURE 3

RECOVERABLE OIL AT CAVITATION



Comments

The following points summarize the important findings of our calculations:

- The residual oil is a small percentage of the stored oil capacity even at the largest appropriate flow rate (less than 1.5% of the initial oil inventory).
- Decreasing the pump rate decreases the residual oil fraction.
- Curvature of the oil surface is most pronounced at the largest pump rate, but even then the difference between normal and critical depths is small (1.23 ft.).
- The higher the pump rate, the less time required to recover the oil inventory. However, a high pump rate leads to a larger residual oil fraction at cavitation.
- The depth of the oil at the brink of the sump is slowly varying for all pump rates examined.

Suggested Recovery **Pumping** Scheme

Suggested Drawdown

In order to minimize the time needed for oil recovery at Weeks Island, the pump rate should be as high as possible. When the depth of the oil at the brink of the sump is about 6 inches, the pump rate should be decreased in order to prevent pump cavitation and to allow recovery of additional oil.

The following sequence represents one possible pump scheme designed to reduce the recoverable residual oil to less than **.2%** of the total initial oil recovery for an initial pump rate of 590 MBBL/day. (Variations in floor elevation may preclude recovering more than 99.8% of the recoverable inventory).

1. Pump at a rate of 590 MBBL/day until the depth of the oil at the brink of the sump is a little greater than the critical depth (about 6 inches). This will require just under 122 days of pumping (time to empty the upper region is included in this value). At the end of this time there will be about 873 MRRL of recoverable oil in the facility.

 continued

2. At about 122 days reduce the pump rate to about 231 MBBL/day.
3. Stop pumping when the depth of the oil at the brink of the sump is .21 ft. This will take an additional 1.7 days of pumping and will lead to the recovery of an additional 384 MBBL of oil.
4. At the end of the above pumping period, reduce the pumping rate again; this time to 76.9 MBBL/day and pump for about 3 days (reduce the depth at the brink to .l ft.). This step recovers an additional 239 MBBL of oil. The oil remaining at this time is about 250 MBBL.
5. Finally, reduce the pump rate to 38.5 MBBl/day and pump for an additional 2.2 days. Yc goes down to .06 ft. and the remaining volume of oil is about 165 MBBL (approximately .2% of the initial inventory).

Reducing the pump rate further may not lead to additional recovery because of local variations in the floor elevation.

More Detailed Modeling

In order to solve the Weeks Island dtawdown with more detail, the following set of partial differential equations can be solved:(5)

$$\frac{\partial Q}{\partial X} + \frac{W \partial y}{at} + q = 0$$

$$S_o - S_f = \frac{\partial y}{\partial x} + \frac{\partial 1}{\partial g}\left(\frac{V \partial V}{\partial x} + \frac{\partial V \partial Q}{A \partial x} + \frac{}{at}\right)$$

where

Q = $W * V * Y$ = channel flow

V = velocity

q = source/sink term

S_f = channel friction slope

S_o = channel bed slope

Even with an accurate solution of the above equations, the final answer will probably be in error due to approximations necessary in defining an equivalent channel for the Weeks Island wall/pillar geometry.

continued

Note

It might be possible to solve the problem more accurately using a matrix open channel solver and modeling the wall pillar geometry exactly. However, due to time constraints this approach was not deemed practical.